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Critical raw materials: A perspective from the materials science community

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ABSTRACT

Functional materials are crucial to meet today's societal challenges and needs, such as the transition towards low carbon energy production to reduce climate change, renewable energies and green economy, clean mobility and improved communication. In order to fulfill specific functions, many of these materials require a variety of specific metallic elements whose total reserves in primary deposits on the planet are limited in quantity and unevenly distributed, respectively require significant efforts for exploration and investments in their exploitation. Furthermore, the extraction and processing of the corresponding metallic minerals can be sometimes related to a high environmental burden as well as frequently negative social impacts. While in contrast to fossil fuels mineral materials can be principally recycled and hence kept as resources, closing the materials loop especially for many specialty metals today is often hampered by dissipation as well as by physical and economic challenges. These metallic elements are also listed under "critical raw materials" which have been receiving increased attention in scientific and policy-related debates over the last decade and years. In this paper, we introduce the topic of materials criticality for the special issue of *Sustainable Materials and Technologies* and observe how the criticality of raw materials is perceived and handled within Materials Science. For this, we (i) present examples of critical raw materials in advanced technologies, (ii) summarize some definitions of criticality, (iii) outline the topic of critical raw materials in the Material Scientist community by highlighting relevant outcomes of a survey on critical raw materials for materials scientists, and (iv) conduct a literature research on "Critical Raw Materials" and "Criticality" in search engines commonly used by materials scientists. The results show that material scientists seem frequently not concerned with the criticality of raw materials in their work, and that the relevant terms appear for a broader scientific community mainly in the fields of environmental science, chemistry-related processing and environmental and resource management. The paper presents and discusses these results and suggests to advance the implementation of the concept of materials criticality in materials research and development.
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1. The importance of critical raw materials to advanced technologies

The present materials paradigm is based on a linear 19th and 20th Century model conceived for a significant smaller world population and implicitly ignoring the limits of earth resources and the impact of

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resource consumption on our climate. It is overdue to introduce a new paradigm to maximize the circularity of existing materials uses and to explore novel approaches for smarter renewable materials, taking at the same time the limited availability of some materials into consideration: the environmental footprint of their supply as well the geopolitical and social constrains for some ores and elements, the so-called "critical raw materials" (CRM).

The increasing need for advanced materials and components that enable certain functions for a variety of important applications, a growing world population and the fact that our earth's resources are limited raise the question of future material supply. Increasing consumption, and changes in the global economic, financial, and political environment led to supply-demand imbalances of certain raw materials, resulting in price volatilities on material markets and creating uncertainties for technologies and their go-to-market strategies. While the construction and transportation sector is looking for mass metals such as copper, zinc, aluminium, lead and steel, as well as sand, limestone, and other aggregates and industrial minerals, new technologies require specific elements such as rare earth elements (REE), platinum group elements, and other technology metals including cobalt, silver, tantalum, titanium, and tungsten [1]. Future supply of these materials has received increasing attention over the last years, with the term "critical raw materials" finding its way into the public debate and various policy actions to tackle our society's future materials demand. The aim of this paper is to depict the material scientists and engineers view and perception in the field of CRM.

The main trends in Europe with impact on raw materials are the transition towards sustainable energy applications through photovoltaics and wind resources, developing and implementing new concepts for transportation by stimulating the development and increasing the market share of electric vehicles, and advancing the use of information and communication technology (ICT) and sensor technology. All these technologies are related to the grand societal challenges, which are climate change, mobility, health, and the need for new concepts of urban development. Such advancements will be accompanied by the demand for more raw materials, and especially those classified as "critical". Fossil fuels such as coal, oil, and natural gas are limited, non-renewable resources, and are aimed at being replaced globally by renewable alternatives to mitigate the negative effects of climate change.

Energy is the basis of industries, global economy, transport, communication, expansion of large cities, and the overall wellbeing of societies. The US Energy Information Administration (EIA) reported that the total global consumption of marketed energy will expand by approximately 48% in the next 20 years until 2040 [2]. While oil accounts for a third of global energy consumption, renewable power (excluding hydro) accounts for only 4 to 5% but grew by 14.1% in 2016 (the largest recorded increment), of which wind energy contributed with more than half, and solar energy almost a third. Renewables became the fastest growing energy source again in the last years and China is overtaking the United States to become the world's largest generator of renewable power [3]. In the context of such a profound transformation of the energy systems in Europe, Asia and North America, the demand in new technologies for wind power, solar power, and hydroelectric power, as well as for electro-mobility is continuing to increase significantly. Europe is leading in renewable energy and has as a target to achieve a share a share of 50% renewable electricity by 2030 [4]. The demand for tellurium, indium, gallium, dysprosium, and neodymium is very likely to increase significantly in the European Union in the coming years, due to the demand from companies active in the solar and wind sectors [5]. To which extent this increase finally will take place can only by estimated on basis of scenarios for future technology deployment and product composition. Here, the bottom line metals demand will depend on a number of factors, some of which are interdependent. As an example, a driving force for the demand of renewable energy generation (i.e. PV and wind) will be the growth of population and wealth but also the energy need from other future technologies such as electro-mobility. In the case of PV, different technical solutions exist (crystalline silicon, CdTe, CIGS, …), and depending which shares these will have in future there will be differing resulting demands for individual metals such as tellurium, indium or gallium. Moreover, advances in material sciences can lead to substitution and higher material efficiency, and successful recycling at end-of-life of these products can reduce accordingly the demand growth for primary metals.

While some of the elements used in these applications can also be found in Europe, over 90 % of REE used in the permanent magnet generators of wind turbines, such as neodymium and dysprosium, are currently mined in China, who owns as the only country in the world a complete mine-to-magnet value chain [5]. Increases in consumer demand, technical innovation and financial speculation caused peaked prices of many metals in 2011/12, particularly those with restricted exports or other kinds of supply limitations. Restrictions on the Chinese export of REE between 2010–2014 triggered a broader awareness and initiated policy initiatives. As a result, the prices of these elements increased by about 10 times (praseodymium) and 40 times (dysprosium) from mid-2010 to the end of 2011. Subsequently, the prices of REE declined again, and most of them are currently not more than double the price as compared to 2010 [6]. The same applies for many other metals such as nickel, zinc, copper, silver (see for example [7]), due to a slowdown in economic growth (especially of China), partial increasing efficiencies in material use and recycling, and reduced speculation activities, as shown for nickel and zinc [8]. However, the temporary relief in metal markets can turn again into a period of price increases or even imminent supply shortages, and first signs for rising prices currently occur for a number of metals [9]. For example, prices for cobalt and lithium, both needed for rechargeable batteries for electromobility and energy storage, have increased significantly between beginning of 2016 and end of 2017. Li-Ion batteries in (hybrid) electric vehicles are an important product towards a low carbon energy approach; their battery packs weigh from 30 kg for hybrids up to over 500 kg for full electric vehicles, depending on the battery capacity respectively cruising range,[1] requiring cobalt, lithium, nickel, manganese, and natural graphite.

Taking the example of photovoltaics, depending on the type, silicon, gallium, indium, and/or tellurium is needed, as well as silver, which is required for rear contacts. Political incentives to make solar harvesting commercially viable have led to a rapid increase of photovoltaics proliferation in many industrialized countries; in Germany, for example, the power plant equivalents raised from 1000 in the year 2000 to over 1.5 million [10]. Such a dramatic change in the political and legislation environment and the societal behaviour has a high impact on the demand of materials necessary to react on the request for a reliable product with high performance regarding the desired functions. Concerning photovoltaics module production in 2015, China and Taiwan hold the lead with a share of 67%, followed by Rest of Asia-Pacific and Central Asia (ROAP/CA) with 14%. Europe contributed with a share of 5% (was 6% in 2014) and North America with 3% [11]. Gallium and its compounds such as gallium-arsenide (GaAs) are important not only in thin-film photovoltaic cells but also in numerous electronic applications [12]. Germany is one of the major recyclers for gallium, and most of the recovered gallium comes from the production residues of gallium used in the epitaxy process for making semiconductors [13]. Gallium will be used even more frequently for semiconductors in the future as light emitting diodes (LEDs) become increasingly important in smart cities, new transportation technologies, and ICT.

[1] Per kWh of battery capacity between 0.15 and 0.4 kg of Co are used in typical NMC type Li-ion batteries, depending on the ratio between nickel (N), manganese (M) and cobalt (C). The cathode development moves towards the lower side of the range, e.g. NMC 622 to NMC 811 which corresponds for a 75 kWh long distance full electric vehicle with a Co content of over 12 kg, a big number of battery cells and a high weight of the total battery pack. In contrast, a 10 kWh battery pack used for a low electric range plug. A hybrid electric vehicle may contain only 1.5 kg Co, less cells and a much lighter battery pack [60].

The "Report On Critical Raw Materials For the EU" [14] showed that China is today clearly "the most influential in terms of global supply" (99% of heavy REE, 87% of light weight rare REE, 87% of antimony and about 11 other elements) beside some other countries such as the USA (90% of beryllium production) and Brazil (92% of niobium production). Any change in the geopolitical-economic framework, e.g. trade barriers, would have an impact on the supply and consequently affect the price of raw materials pertaining to the corresponding elements. Therefore, the European Commission has launched the EU Raw Materials Initiative in 2008 and published reports on CRMs in 2010 [14], 2014 [15] and 2017 [16]. The list of CRM prepared in 2010 contains 14 critical elements, whereby the Platinum Group Metals (PGMs) and the rare earth elements are summarized as one raw material each. In total, 37 elements were described as critical (see Table 1). In the report of 2014, six other materials - borates, chromium, coking coal, magnesite, phosphate rock and silicon metal - were added to the list, tantalum was removed, and a distinction between light and heavy REE was introduced. A new EU list of CRM was published in the autumn of 2017, and 9 new elements/compounds were added to the list. It is interesting to note that chromium, magnesite and nickel are not further mentioned in the 2017 list. Changes in the list are also related to the refinement of the methodology to define critical materials. The methodology used by EU for the list 2017 and the changes regarding the list elaborated in 2010 and 2014 are explained in detail in the report of Blengini et al. [17]. The developed method tried to ensure the highest possible level of comparability with the 2011 and 2014 lists and the term criticality is seen as a "snapshot in time" of the current raw materials situation.

2. Definitions of criticality

What does the term "critical elements" or "critical (raw) materials" mean and what makes materials critical? The existing overviews of methodologies on criticality assessment and reviews on existing publications are manifold; a few examples are[9,24–26,35,40–42,48–51],59, and [61].[2] With this paper, we do not want to add another review, but limit ourselves to observing that approaches on criticality are usually estimations based on probabilities and long-term and interrelated developments, and provide a brief overview on their evolution: Gordon et al. [18] came in 2006 to the conclusion that no immediate concern exists about the capacity of mineral resources to supply requirements for geochemically scarce metals, but that limitations could arise from restrictions on international trade or legislative restrictions. Since then, a variety of methodologies to assess materials criticality have been developed. Glöser et al. [19] categorize the literature on materials criticality into four classes: (i) local, such as an enterprise, (ii) nation-wide, (iii) economic region, such as Europe, and (iv) on a global level. Most criticality studies follow an approach analogous to a classical risk assessment, a proceeding first introduced by the US National Research Council [20]. They use the main matrix of a potential of risk (e.g. supply risk and all subcategories that should be considered) against vulnerability, i.e. the importance of a raw material for a specific area, the impact of the material on lowering the performance of the economy, slowing down or even ceasing technological progress. Graedel et al. have coined the term "critical" in the United States on things or occurrences that are essential, important, crucial, or significant for influencing factors such as the environment, society, or economy. They established a criticality matrix to "provide a framework for federal agencies, decision makers, the private sector, and any users interested in minerals to make assessments" for the long term, whereas criticality is regarded as a continuum of possible degrees [21]. They also extended the approach of the National Research Council by a third component, environmental implications [22].

Important authors who started discussions on CRMs in Europe were, amongst others, Angerer et al. [23] who studied emerging technologies in various industrial sectors and assessed present and future raw material requirements for the most important ones. The EU Ad-hoc Working Group with expert members from various private and governmental European organisations then discussed in 2010 the term "critical raw materials" as the dependence between economic importance and supply risk. For estimating the supply risk, the Group took into account various factors such as the producing country's socio-economic stability, the concentration of producers by one country, or current technologies to substitute or recycle such elements within Europe. The "environmental country risk" assesses risks that might occur if the producing country does not take sufficient care to ensure a sustainable production of the element, e.g. by protecting the environment. This kind of supply risk is then related to the economic importance of the element for the country or countries observed. Glöser et al. [19] mention two more existent general approaches to assess raw material criticality: a single risk index calculated from sub-indicators, or scenario and time series analyses to forecast demand and supply developments. The scenarios are related to the requests of the stakeholder groups for which such risk assessment and forecast is a crucial tool in short- to long-term strategies.

Criticality is thus a complex concept and in no way unambiguously defined. Also, a material is not critical per se and does not necessarily remain critical for a long period. "Critical raw materials" describe elements that at a given time and within a given economic system are necessary for achieving certain performances and functions in a technology or product, and for which the supply of this element therefore is crucial. The term "critical" is thus strongly related to the discussion of medium- and long-term economic and technological strategies and their advantages or disadvantages in a global competition. A classification of a raw material to be "critical" differs fundamentally from attributes such as materials properties, which can be directly linked with a material.

Table 1
List of critical raw materials at EU level (in alphabetical order), listed from EU reports 2010 [14], 2014 [15] and 2017 [16].

List of critical raw materials at EU level (in alphabetical order)		
2010	2014	2017
Antimony	Antimony	Antimony
		Baryte
Beryllium	Beryllium	Beryllium
		Bismuth
	Borates	Borate
	Chromium	
Cobalt	Cobalt	Cobalt
	Coking coal	Coking coal
Fluorspar	Fluorspar	Fluorspar
Gallium	Gallium	Gallium
Germanium	Germanium	Germanium
Graphite	Graphite (natural)	Natural graphite
		Hafnium
		Helium
Indium	Indium	Indium
Magnesium	Magnesium	Magnesium
	Magnesite	
Nickel	Nickel	
Niobium		Niobium
Platinum group metals	Platinum group metals	Platinum group metals
	Phosphate rock	Phosphate rock
		Phosphorus
Rare earths elements	Heavy rare earth elements	Heavy rare earth elements
	Light rare earth elements REEs (Light)	Light rare earth elements
		Scandium
	Silicon metal	Silicon metal
Tantalum		Tantalum
Tungsten	Tungsten	Tungsten
		Vanadium

[2] A recent overview of publications on criticality, compiled by international experts in the fields, has recently been established by the International Round Table on Materials Criticality IRTC. The collection can be downloaded as a RIS file on the projects' homepage, www.irtc.info.

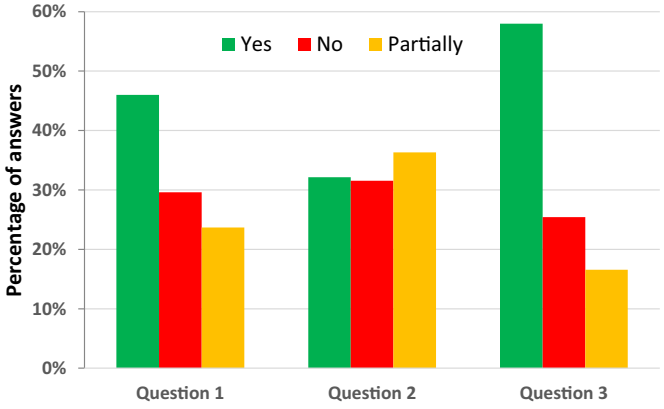

Fig. 1. Results of a survey on knowledge in "Critical materials". 169 answers from European material scientists in academia (Source MatSearch with support of Federation European of Material Science (FEMS) and Entwicklungsfonds Seltene Metalle (ESM)). Question 1: "In your R&D work or projects, has it ever been an objective to take into account future availability of the materials you are using?" Question 2: "Do you know the origin of materials you are working with (mining company, country)?" Question 3: "In your R&D work or projects, has it ever been an objective to take into account price development of the materials you are using?"

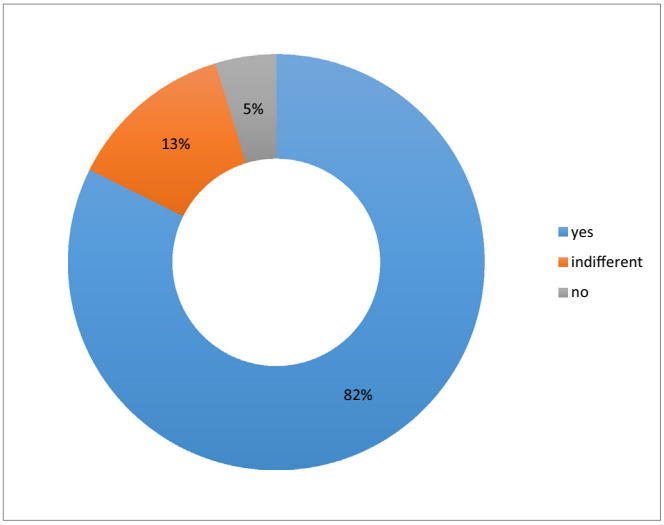

Fig. 2. Answer to the question if materials courses syllabus should explicitly include social responsibility (CSR) issues, environmental issues and the resources thematic (170 answers).

Materials science is of essential importance to assess the necessity of certain raw materials in a component or product and possible substitution potentials. A risk assessment of the raw materials in functional materials, components and products could help a company take appropriate precautions regarding the choice of materials, design, and processing to reduce the use of such elements or secure their persistence in the materials cycle to secure supply and increase sustainability. It would therefore be important for materials scientists to have a basic knowledge on the criticality of materials, since they are the ones who know the composition of the materials, necessary and desired properties to achieve, and so on.

3. Perceptions on critical raw materials by the materials science community

Material scientists are used to describing materials on the level of their microstructure. Metallic alloys e.g. consisting of a mixture of two or more metallic elements or a mixture of metallic and non-metallic ones. From the point of view of a material scientist, it is important that the composition of a material, together with the manufacturing process, leads to the desired properties and functions in a component and thus to a superior performance of the end product, which is why we also speak of advanced, functional, intelligent or structural materials. The functions rely on the composition of the elements and phases, on the purity and on the processing of the material e.g. by heat treatment, forging or other transformation processes.

Raw materials are a source for elements to be used for advanced materials, which have tailored properties and functions needed in certain components or systems.[3] Neodymium-Iron-Boron (NdFeB) permanent magnets serve as an illustrative example to explain the view of material scientists. The emerging trend towards the use of electric motors and generators in the renewable energy and mobility sector has led to increases in the demand expectations and foreclosure of markets by providers. Neodymium increases the remanence and coercivity of magnetic materials, and can be further combined with dysprosium to preserve these elevated magnetic properties even at high temperatures [27]. These favourable properties had an impact the price of neodymium, dysprosium and praseodymium, which was very volatile during the last years, especially during the period of 2011 to 2014 [28].

In principle, two possibilities exist for obtaining the starting materials: mining and transformation of the ores into the corresponding metals and compounds (Nd, Fe and Fe_2B), or recovering of the material from the used magnets [29]. When using REE from used magnets, the elements and compounds are mixed in the correct composition, melted and solidified in an ingot (coarse grained material) or spin-melted (nanosized and amorphous materials). The spin-melted material is then heated again to full crystallize it and additional grinded to flakes. This material is subsequently coated for protection against oxidation and mixed with polymers for further shaping. If a powder metallurgical route is chosen, the raw material is melted, solidified in an ingot, fully crystallized, and grinded and jet-milled into micron-sized powders. After pressing, sintering and additional annealing at around 600 °C, the final magnets have to be coated with nickel against oxidation and corrosion. As a by-product, hydrogen decrepitating produces very brittle material from the casted ingots, which can be further used for powder metallurgical processes. Later on, the used magnets could, from a technical point of view, easily be integrated in the production process by adding to the melt or using hydrogen decrepitation [30]. When using this route, the original material composition of the final product is only slightly altered, and for some applications (e-motor) the properties are even superior. An alternative way, more complicated and expensive, is the production of pure elements from the used magnets. Both ways of recycling are well developed and their up-scaling approved [31,32,33,34]. Under the German r4 research funding initiative the SEMAREC project (Seltenerd-Magnet-Recycling) aims to develop an industrial pilot scale process capable of treating economically a broad variety of NdFeB magnet production scraps and end-of-life materials to produce larger tonnages of rare earths mixed oxides, with a focus to optimise the overall process chain and its interfaces (mechanical treatment, hydrometallurgy, separation and purification).[4] From a material science perspective, NdFeB magnets are still a very interesting research field, but are not commonly regarded as being an issue of current or future concern. This is also reflected by the number of publications, which have not shown any major fluctuations over the last years [35].

[3] Advanced materials perform functions that are specific or new in contrast to conventional material. They are versatile in their applications and crucial for novel technologies. Advanced materials are mostly related to new manufacturing technologies to achieve such tailored properties. A good example is nanomaterials with very specific properties only in the nano-size.

[4] https://www.r4-innovation.de/de/semarec.html (Accessed 6.7.2018).

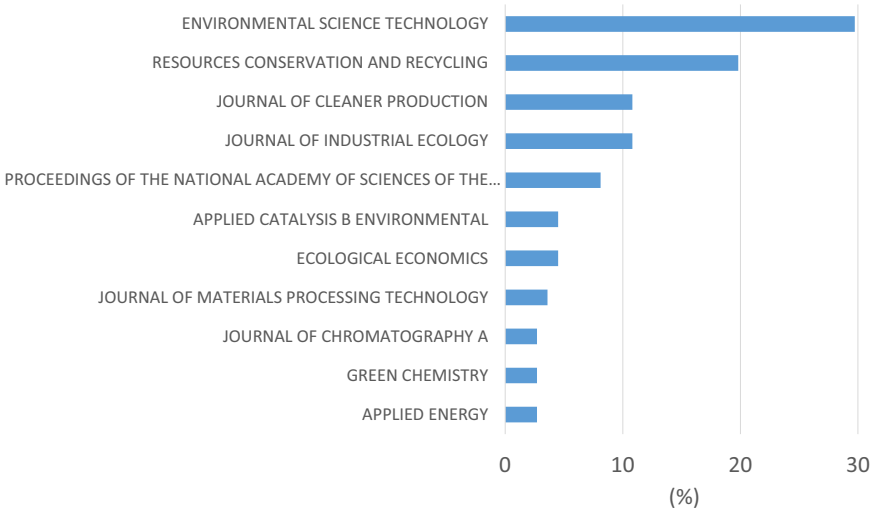

Fig. 3. Result of literature search in Web of science using research terms linked to critical raw materials (period 1900–2017).

In spite of its basic necessity to produce any advanced material, and although materials scientists are usually the ones who have the knowledge to assess ways of recovery and their efficiency – as in the magnet example – as well as substitution potentials, the question of raw materials supply is surprisingly underrepresented in the materials scientists community. In a survey on "Awareness on use of 'critical raw materials' in education and research", carried out by MatSearch Consulting with support from the Federation of European Materials societies (FEMS) and Entwicklungsfonds Seltene Metalle (ESM) [36], it was revealed that not even half of the surveyed researchers (47%) have taken in account the future availability of the materials used for their research projects (Fig. 1). As few as 33% of the surveyed researchers know the origin of the used material, an important fact regarding the estimation of future supply risk in case of success of the research project and the transfer into a future market. Less surprising is the result that a majority (58%, 98 answers), in contrast, mentioned that they take into account price development of the materials they are using for their research. Additional 17% answered that they do it depending on the project and the materials used. In those cases in which additional comments were given, the respondents stated amongst others that e.g. "toxicity, price and availability of the materials are the key factors in the searching of new materials", that they look for "material source security for production", "substitute critical or expensive materials by others" or are even "developing decision tools to consider critical materials".

Surprisingly and maybe in contrast to the results presented in Fig. 1, it seems that a clear consensus exists regarding the need to include topics such as social responsibility (CSR) issues, environmental issues and the resources thematic in the material science syllabus (Fig. 2). Various materials scientists and engineers active in teaching mentioned that topics such as substitution of certain elements and recycling are already part of the materials courses; however, these topics seem mostly not explicitly mentioned in the course description. It was also frequently indicated that collaborative projects in materials research and development are more and more expected by the funding agencies as well as involved industries to take into account sustainability considerations about the materials in the component parts and devices, as well as environmental impacts.[5]

A risk assessment of the raw materials in functional materials, components and products could help to complement such sustainability considerations and assist companies in taking appropriate precautions regarding the choice of materials, design, and processing to reduce the use of such elements or secure their persistence in the materials cycle to secure supply and increase sustainability. If formulas for criticality are used for specific components, products, or systems, calculations can only reach a higher precision if details and facts of the composition and also possible alternatives are available.

4. Perspective on the literature

As mentioned before, there are numerous comprehensive reviews on existing criticality studies, conducted from a variety of perspectives, general ones (see "Definitions of criticality"), but also e.g. focusing on international comparison [41], technological sectors [52] and other selected aspects. The research conducted in this paper aims at a) providing an overview on the development of publications in the area of CRM as recorded in two databases commonly used by materials scientists and engineers,[6] and b) answering the question why the topic of CRM is not very well known in the material science and engineering community. For this, we searched Google Scholar and Web of Science for the terms "critical materials", "critical raw materials", "strategic materials", "strategic raw materials", "scarce materials", "scarce raw materials" and "criticality" (in combination with (raw) materials). Fig. 3 provides an overview of the total number of cited publications in Web of Science. Since the search terms are also often used in other fields, publications with search terms related to radioactivity, medical applications and other frequently used contexts were excluded.[7]

Fig. 3 also shows that search terms combining "raw" with "criticality", "strategic" or "scarce" leads to only a few number of publications (105) between 1900 and 2017. "Strategic" only produced nine results, mostly related in the defence/military context; "scarce" few more. When searching for "critical", including "strategic" or "scarce" raw materials in Google scholar, 2'851 results were generated. Evidently, the two databases lead to different results because Google Scholar is

[5] The prevalence of these questions depend amongst others on the life-time of the end product: materials for computer and cell phones only have a short life time of a few years, so recycling and substitution of critical materials is a more important question than e.g. in the area of household machines or cars, which should be reliable for at least 10 to 15 years, or even longer in the case of aircraft or construction materials (e.g. bridges or houses).

[6] On the target groups and coverage of Web of Science and Google Scholar see e.g. [62,63].

[7] Added to the search field: NOT radioact* NOT shear NOT medic* Not turtl* NOT animal* NOT snake* NOT drone* NOT social NOT failu* NOT plasmonic* NOT socio* NOT fract* NOT nonlinear* NOTgenet* NOT mental* NOT brain* NOT dielectric* NOT cognit* NOT psych* NOT nano* NOT deformat* Not stretch* NOT superconductor NOT pharma* NOT nuclear* NOT microstructur* NOT fatigue* NOT bio* NOT cell* NOT properti* NOT quantum*) NOT TITLE: (nonline* OR woman) NOT PUBLICATION NAME: (genet* OR sociol*).

searching in the whole internet including full texts without any quality criteria, whereas Web of Science is listing a selection of only peer reviewed journals. A large part of the literature on CRM is not published in scientific journals but in reports of institutes, NGO's or governmental bodies. This result shows that the discussions regarding criticality of materials/raw materials are driven by governmental needs and that the scientific background is still in the developmental stage.

Fig. 4 shows the development of publications over time for the mentioned search terms ("criticality" and "raw materials" were not introduced because the results are included in the other search results). Using the term "critical materials" in a literature search revealed that only very few papers and reports were already published before and in the 1980s [37,38]. An article in *Science* on "Critical Materials Imports Vulnerable, OTA Warns" [39], published in 1985, reported that the US are "likely to become more dependent on imports of critical materials from potentially insecure sources of supply" and "more and more vulnerable to a disruption of imports" regarding elements such as chromium, cobalt, manganese, and platinum metal group metals with productions concentrated in South Africa and the Soviet Union. It is mentioned that the US government already held a stockpile of strategic materials in 1939. This was maintained to meet military and other critical needs (in this context the expression "strategic materials" is used). However, the industry was not in favour of creating such stockpiles for civil needs. In Europe, the scarcity of strategic materials during and after World War II was also a topic (e.g. aluminium), however due to the economic upturn and the focus on peace and common commercial politics the discussion started only in the beginning of the new millennium and was related directly to the supply risk for Europe, geopolitical issues and the discussion around climate change.

In the beginning of the 21st century, Web of Science records a drastic increase of the number of articles with the terms "critical materials" and "critical raw materials". Publications with "critical raw material" as a key term began to grow significantly after 2011 (Figure 4). An investigation of the publications listed in Web of Science using the terms "critical materials" and "critical raw materials" shows results indicating that there are essentially two main clusters of researchers dealing with this topic (see Figure 5): a first one consisting of research groups strongly interacting with Thomas E. Graedel from Yale University, and a second one in Europe around Jo Dewulf from European Commission–Joint Research Center (JRC), Institute for Environment and Sustainability, Ispra, Italy. However, important other research groups are missing, such as the research activities revolving around GE global research (e.g. Steven Duclos and Anthony Ku [52,53,61]), the Critical Materials Institute's work, lead by a variety of actors such as Roderick Eggert [55] who was already leading the first NRC approach [20], or the groups around Gabrielle Gaustad, RIT [54], or Elisa Olivetti, MIT [56].

Most of the papers are published in journals with a focus on environmental science, technology, and production (Fig. 6). Only very few are within the material science and engineering communities, such as Metals Progress, Journal of Electronic materials or JOM and MRS Bulletin. It is to mention that these journals have a low impact factor (<2) and are not of general interest in the mentioned community. The journals which show the highest publication rates for papers on CRM are mostly in the area of environmental science and sustainability, such as "Environmental Science and Technology", "Resources, Conservation and Recycling" and "Journal of Cleaner Production". Industrial Ecology is represented by the "Journal of Industrial Ecology"; other disciplines are covered in journals with a special focus on environmental issues and special fields in chemistry related to pollution or green energy topics such as "Ecological Economics", "Green Chemistry", or "Applied Catalysis B: Environmental".

Materials scientists and engineers, though, are mostly not occupied in their research with political or environmental issues unless the development revolves around material and material processes that could be detrimental to human health and the environment or whose installation would also be suitable for military application. However, with new processing techniques, industry demand for sustainable material solutions for innovative products, and significant price volatility of certain key raw materials for such new products, material scientists have recently also been increasingly confronted with sustainability concerns. When it comes to CRM, there is apparently not yet sufficient incentive for the topic to be dealt with in important material journals. This is

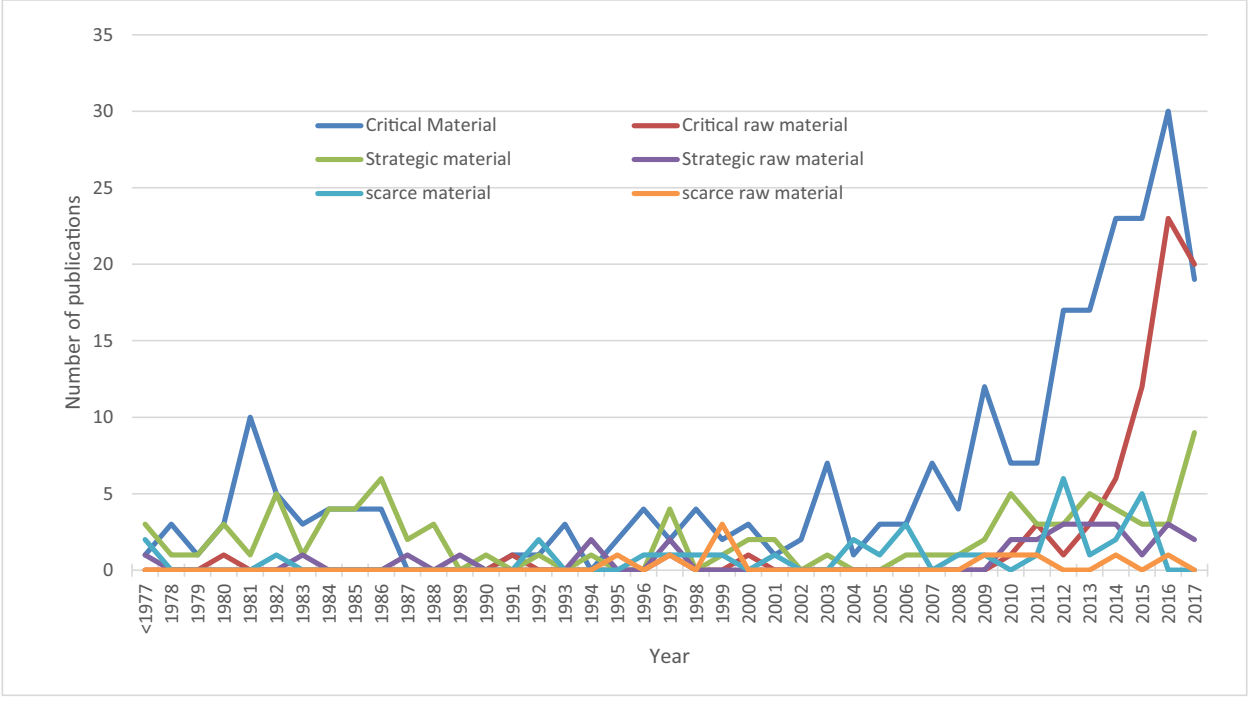

Fig. 4. Yearly publications of papers dealing with critical (raw) materials (Web of Science) (Research terms as in Fig. 1).

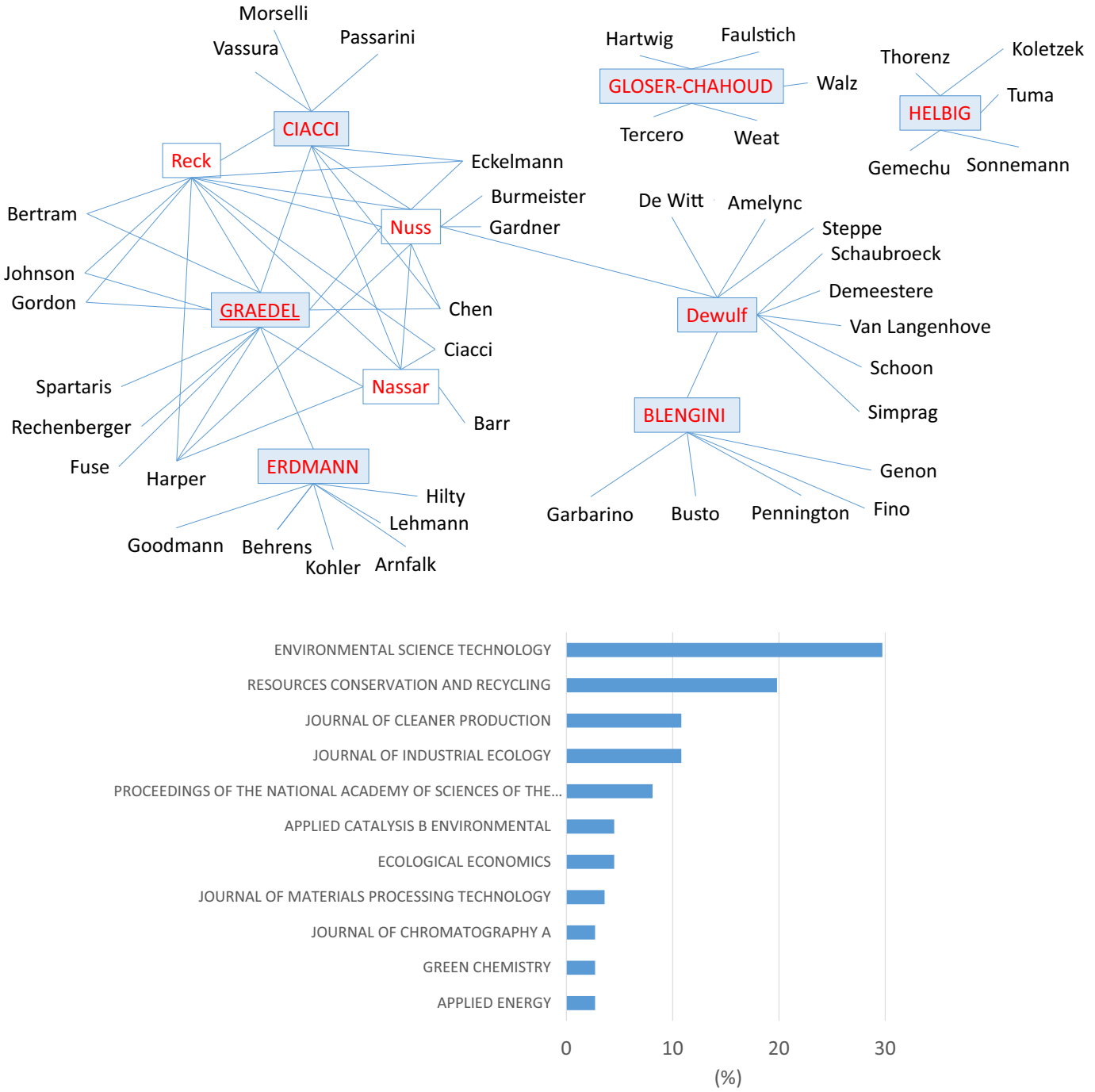

Fig. 5. Cluster of research groups dealing with "critical materials" and "critical raw materials" published in journals cited in the Web of Science. Names are shown if more than two common publications exist.

the case despite the fact that there seems to be a general interest of the materials science community to include resource issues and the discussions surrounding them in their research and curricula.[8] Since the community has their specific journal groups, formats of cross-sectional research are also rarely published. Integrating the demand side better into criticality assessment is an issue that is discussed for a few years by now. Although this work is not finished yet, it is an ongoing debate (see e.g. [57] and statements from the recent first edition of the "International Round Table on Materials Criticality" IRTC on June 19, 2018).[9] Other, partially very recent publications have already advocated for a more in-depth implementation of criticality in engineering disciplines, such as Graedel and Nuss [58] and Peck et al. [43] who observe materials criticality from a product design perspective, and Helbig et al. [44] who highlight the benefits of a resource strategy concept for sustainable materials research and development.[10] It would be desirable to give this transdisciplinary research a stronger voice.

[8] Bustamante et al. mention in their short paper on "Criticality Research in the Materials Community" that "it is paramount that we as members of the materials community recognize the amount of leverage we have to address future issues of materials criticality" [60].

[9] www.irtc.info.

[10] [43] is also part of this special issue of *Sustainable Materials and Technologies*.

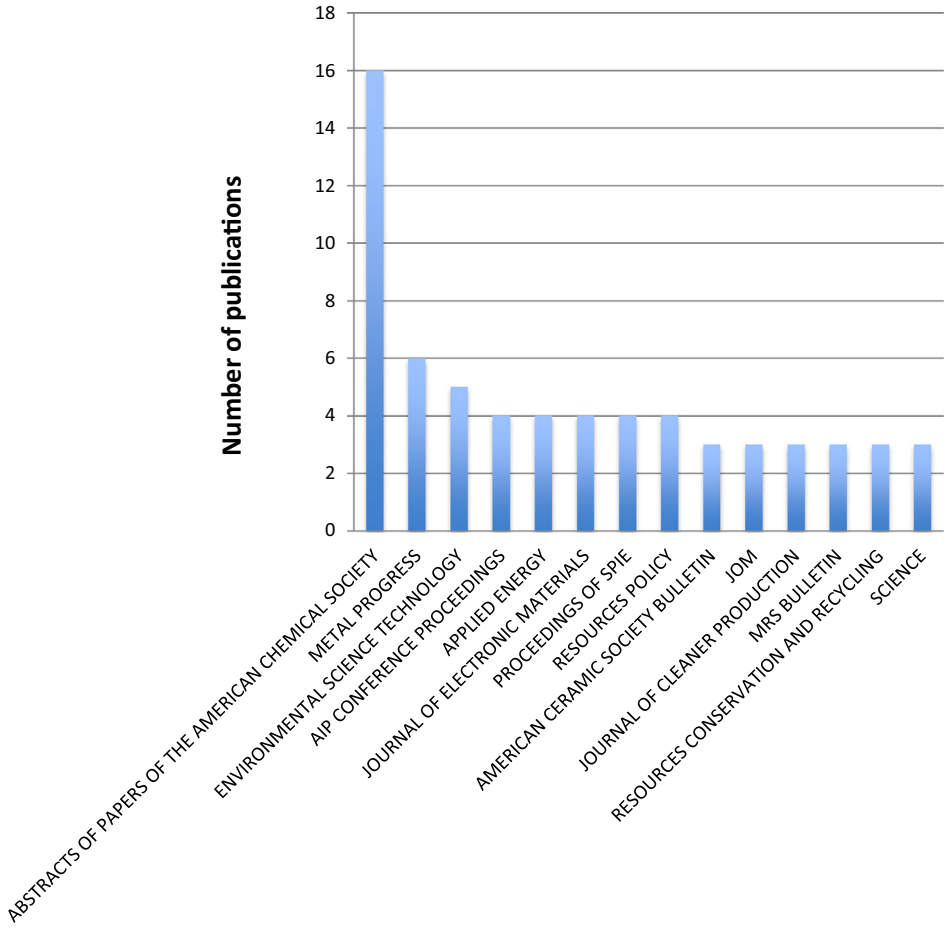

Fig. 6. List of journals for publications in the field of critical materials, 1990–2017, as listed in Web of Science.

5. Conclusions and outlook

Today, we relate the term "critical raw material" not only to questions of geology but also to other areas such as politics, geopolitics, economy, environmental and social considerations as well as to various disciplines in basic research, science and engineering. The European Commission and the Parliament discuss "societal challenges" which include fundamental current topics such as climate action, food security and efficient energy [45]. Besides being listed as a societal challenge on its own, there is almost no topic which is not related to and depending on secure, sustainable and reliable raw materials supply for advanced materials and related higher technology applications. Industries have started to adopt concepts related to CRM such as lifecycle management to monitor products along their value chain through design, manufacturing, maintenance, disposal and recycling. Although scientists have attempted to create awareness on the issues, such assessments have not yet been fully taken into account in material research and development.

Most of the literature on CRM is published in journals that do not usually consider materials development, and materials-related journals and researchers focus on this issue only in niche topics such as the substitution of critical elements by more abundant ones. In addition, most of the important publications in the field of CRM are not listed in Web of Science, the commonly used literature search tools in materials science and engineering. Related research topics include the recycling of materials and elements, mostly discussed in ecology-related journals, which are rarely consulted by materials scientists. An implementation of the topic within the engineering community is apparently lacking.

Considering material criticality implies discussion with experts from different industrial sectors, scientific backgrounds, and especially with the society represented by national and multinational governmental and non-governmental organisations. CRM have taken their place in the European research and development sector in the EU, US and Japan.[11] Negative scenarios where industries and large research communities have a competitive disadvantage vis-à-vis other national, European or global players could be avoided by an increased awareness of possible risks due to criticality of materials. Research and development programmes in industries should follow the concept of life cycle management more strongly to avoid such negative scenarios. The debate on CRM has shown that experts from various stakeholder groups and especially the industry should rethink technology and product strategies and consider the criticality of materials and processes as a central issue of management.

The assessment of materials criticality, following mostly the structure of risk assessment theories, is mainly based on estimations; however, in times of "big data", the combination of data at all levels of the value chain (collected by researchers, engineers, designers and other groups) could provide crucial market advantages for regional and national economies. Companies and the society using a product could

[11] Examples are e.g. the European Institute of Innovation and Technology (EIT) for raw materials, and the European research framework Programme including HORIZON 2020. In the context of the market development since the early 2000's, the European Commission started in 2008 the Raw Materials Initiative and later in 2012 the European Innovation Partnership on raw materials, as well as the recent circular economy approach in December 2015. Similar activities were conducted even earlier in the US. Japan and at the UN level (UNEP resource panel) [46,47].

become a match-making entity in which companies allow more transparency about materials and products and their ecological footprints, and the society could be more engaged to feed industry back with valuable secondary and possibly critical materials, thus reducing waste and dissipation.

Future research on the topic could address strategies on how to better implement an awareness on criticality in the materials scientists community and how to address the topic in a way that makes it accessible also for scientists who are less familiar with the in-depths of ongoing developments within criticality methodologies.

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